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**MUSCLE PAIN INDUCES A SHIFT OF THE SPATIAL DISTRIBUTION OF UPPER
TRAPEZIUS MUSCLE ACTIVITY DURING A REPETITIVE TASK: A MECHANISM
FOR PERPETUATION OF PAIN WITH REPETITIVE ACTIVITY?**

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40 **ABSTRACT**

41 **Objective:** An association exists between repetitive movements and neck-shoulder muscle pain.

42 The mechanisms underlying this association remain unclear. This observational study investigated
43 the effect of upper trapezius muscle pain on the distribution of upper trapezius activity during
44 repetitive lifting. It was hypothesized that nociception would change the distribution of activity
45 resulting in activation of muscle regions which would not normally be active during the task.

46 **Methods:** Healthy men repeatedly lifted a box with a cycle time of 3s for 50 cycles, at baseline,
47 following injection of isotonic and hypertonic saline into the upper trapezius muscle and 15 mins
48 after the last injection. High-density surface electromyography (EMG) was recorded from the upper
49 trapezius using a grid of 64 electrodes. The EMG amplitude was computed for each location to
50 form a map of the EMG amplitude distribution.

51 **Results:** During the painful condition, the overall EMG amplitude was lower compared to all other
52 conditions ($p<0.05$) and in addition, the center of activity of upper trapezius was shifted towards the
53 caudal region of the muscle ($p<0.01$), a region not normally active during the task. The described
54 alterations of muscle activity likely play an important role in the perpetuation of pain during
55 repetitive activity.

56 **Discussion:** Novel mapping of the spatial distribution of upper trapezius muscle activity showed
57 that nociception induced a redistribution of activity during repetitive lifting. This knowledge
58 provides new insights into the mechanisms underlying the perpetuation of pain with repetitive
59 activity.

60 **Keywords.** Muscle pain, repetitive work, work-related musculoskeletal disorders, high-density
61 EMG

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69 INTRODUCTION

70 Pain localized to the neck-shoulder region is an increasing problem in both general and
71 working populations ¹. Muscle pain frequently affects the upper division of the trapezius muscle,
72 and patients typically complain of dull pain and stiffness. A prospective study among healthy
73 female packers indicated that within the first year of employment more than 50% of workers
74 develop trapezius myalgia ². Similarly an investigation among both blue- and white-collar workers
75 with pain symptoms in the upper quadrant reported the highest prevalence of myofascial trigger
76 points in the upper trapezius muscle ³. Epidemiological reviews provide strong evidence for an
77 association between repetitive movements, awkward posture, and the development of neck-shoulder
78 muscle pain ⁴⁻⁷. However the mechanisms underlying these associations remain unclear. One likely
79 mechanism could be pain induced changes in neuromuscular control during repetitive movements,
80 for instance to protect the painful region, which could eventually perpetuate the painful condition.

81 Pain within the region of the trapezius muscle is known to limit maximal voluntary
82 contraction, reduce endurance, and induce adaptive changes in muscle coordination during complex
83 tasks ⁸⁻¹¹. Additionally, studies using high-density surface electromyography (EMG) have shown a
84 change in the spatial distribution of trapezius muscle activity during sustained isometric
85 contractions following noxious stimulation of the upper trapezius muscle via injection of hypertonic
86 saline ¹²⁻¹⁴. Furthermore, high-density EMG investigations revealed a different distribution of
87 muscle activity in people with fibromyalgia ¹⁵⁻¹⁶ and that pain prevents the redistribution of muscle
88 activity to different regions of the upper trapezius during sustained shoulder abduction in this
89 patient group ¹⁷. These findings suggest that nociception induces a change in the distribution of
90 upper trapezius muscle activity during isometric tasks leading to suboptimal production of force and
91 potential overload on specific muscle regions. However, whether or not nociception induces a
92 change in the distribution of upper trapezius muscle activity during repetitive tasks is unknown.
93 Such knowledge would further our understanding of the mechanisms contributing to ongoing pain
94 with repetitive work activity.

95 Here we investigate the effect of experimentally induced upper trapezius muscle pain on the
96 distribution of upper trapezius muscle activity during a repetitive dynamic task. High-density
97 surface EMG was utilized to provide topographical representations of the EMG amplitude, and
98 relative adaptations in the intensity of activity within regions of the upper trapezius muscle were
99 quantified. It was hypothesized that nociception would change the distribution of upper trapezius
100 muscle activity resulting in activation of muscle regions which would not normally be active during
101 the task.

102

103 **MATERIAL AND METHODS**

104 *Subjects*

105 Ten healthy male (age: 26.2 ± 3.1 years, height: 178.2 ± 6.3 cm, weight: 71.3 ± 9.2 kg)
106 volunteers participated in this observational study after providing written informed consent. All
107 participants were free of shoulder and neck pain, had no past history of orthopedic disorders
108 affecting the shoulder or neck region and no history of neurological disorders. All subjects were
109 right hand dominant. Ethical approval for the study was granted by the local Ethics Committee
110 (200538) and all procedures were conducted according to the Declaration of Helsinki. All subjects
111 completed the study.

112

113 *Experimental procedure*

114 Subjects attended a single laboratory session were required to lift a 1 kg box between
115 shelves positioned at hip and shoulder height with a cycle time of 3 s for 50 cycles. Subjects were
116 asked to sit tall on an angled cushion positioned on a table, in order to have both legs suspended and
117 avoid possible compensation from leg muscles. An acoustic signal from a digital metronome was
118 provided to the subjects during the task to standardize the duration of cycles. Subjects repeated the
119 task four times: 1. baseline, 2. following injection of isotonic saline into the right upper trapezius
120 muscle, 3. following injection of hypertonic saline into the right upper trapezius muscle and 4. 15

121 mins after the last injection (recovery). The rest interval between the repetitions was set to 15
122 minutes starting from the moment when the pain caused by the injections disappeared. Subjects
123 practiced the movement sequence for ~1 min without the weight prior to data recording.
124

125 *Experimental Muscle Pain*

126 Experimental muscle pain was induced by injection (27G cannula) of 0.4 ml sterile
127 hypertonic saline (5.8%) into the upper division of the trapezius on the right side. Isotonic saline
128 (0.4 ml, 0.9 %) was used as a control injection in a similar location. For both injections, subjects
129 were positioned in comfortable sitting. The location of the injection was defined as 15 mm cranial
130 to the line between the acromion and the spinous process of the seventh cervical vertebra. The bolus
131 was injected over a 10-s period. The isotonic saline injection was given first however participants
132 were blinded to each injection and were told that one or both might be painful.
133

134 *Measures of Perceived Pain Intensity and Area*

135 Participants were asked to verbally rate their level of perceived pain intensity on an 11 point
136 numerical rating scale (NRS) anchored with “no pain” and “the worst possible pain imaginable”.
137 Pain intensity ratings were obtained immediately following the injection and every 30 s until pain
138 was no longer reported. Peak pain intensity and duration of pain were extracted. Participants
139 documented their area of pain on a simple body chart illustrating an outline of a body. Pain
140 drawings were subsequently digitized (ACECAD D9000 + Taiwan) and pain areas measured in
141 arbitrary units.
142

143 *Electromyography*

144 Surface EMG signals were detected with a semi-disposable adhesive grid of electrodes (OT
145 Bioelettronica, Torino, Italy). The grid consists of 13 rows and 5 columns of electrodes (1-mm
146 diameter, 8-mm inter-electrode distance in both directions) with one absent electrode at the upper

147 right corner (Figure 1). The position corresponding to the missing electrode was used as the origin
148 of the coordinate system to define the electrode location. Prior to electrode placement, the main
149 innervation zone location of the right upper trapezius was identified between the seventh cervical
150 vertebra (C7) and the lateral edge of the acromion line with an array of 8 electrodes (silver bars, 5-
151 mm long, 1-mm diameter, 5-mm inter-electrode distance). The electrode grid was placed with the
152 4th row along the line between C7 and the lateral edge of the acromion with the lateral electrode
153 column 10-mm distant from the innervation zone location (Figure 1). The injections were
154 performed lateral to the electrode grid (~ 10 mm) and corresponded to the 4th row of the grid.

155 The subject's skin was prepared by gentle local abrasion (Medic-Every, Parma, Italy) and
156 cleaned with water. 30 μ l of conductive gel was inserted into each cavity of the grid to provide
157 electrode-skin contact. A ground electrode was placed around the right wrist.

158 The bipolar EMG signals were amplified (128-channel surface EMG amplifier, OT
159 Bioelettronica, Torino, Italy; -3dB bandwidth 10-500 Hz) by a factor of 2000, sampled at 2048 Hz,
160 and converted to digital form by a 12-bit analog-to-digital converter.

161

162 *Signal Analysis*

163 Surface EMG signals were off-line band-pass filtered (second order Butterworth filter; -3
164 dB bandwidth, 10-400Hz). 51 bipolar EMG signals along the direction of the muscle fibers were
165 obtained from the grid (13 x 4 bipolar recordings with one absent electrode). Root mean square
166 (RMS) values were computed from each bipolar recording from adjacent, non-overlapping signal
167 epochs of 1-s duration. For graphical representation, the 51 values were linearly interpolated by a
168 factor of 8 but only the original values were used for data processing and statistical analysis. To
169 characterize the spatial distribution of muscle activity, the following variables were extracted from
170 the 51 bipolar signals: RMS averaged over the 51 signals, entropy, and the two coordinates of the
171 centroid of the RMS map (x and y -axis coordinates for the medial-lateral and cranial-caudal
172 direction, respectively) ^{13,18}. The centroid of the amplitude map is the mathematical barycenter of

173 the map. Entropy indicates the degree of homogeneity in activation, with higher values
174 corresponding to more uniform distribution of the RMS values over the grid.

175 Four uniaxial accelerometers (two parallel and two perpendicular to the horizontal plane)
176 were mounted on the box to obtain the start and end points of the cyclic movement. The signals
177 from the accelerometers were rectified, averaged and low pass filtered (Butterworth 2nd order filter,
178 anticausal, 10 Hz cut-off) in order to identify the instant of contact of the box with the shelf. A
179 simple threshold on the resulting signal was sufficient to identify the contact instants of the box
180 with each of the two shelves. This operation was necessary to extract the correct timing of the
181 cycles and to compensate possible errors with respect to the timing provided by the metronome.

182 Each cycle was divided in 10 epochs of equal length and the EMG signals were analyzed
183 separately for each epoch of each cycle. The epochs are indicated in the following paragraphs as
184 percentages with respect to the cycle duration (e.g. 30% cycle indicates the third of the 10 epochs of
185 a cycle). The EMG variables were then averaged across the 50 cycles for each epoch of the cycle.

186

187 *Statistical analysis*

188 One-way ANOVAs were applied to the duration, area and intensity of pain with condition
189 (hypertonic, isotonic) as a factor. Repeated measures ANOVAs were applied to RMS, entropy and x
190 and y -axis coordinates with condition (baseline, isotonic, hypertonic, post) and stage of cycle (10%
191 intervals of the cycle) as factors.

192 Significant differences revealed by ANOVA were followed by post-hoc Student-Newman-
193 Keuls (SNK) pair-wise comparisons. Results are reported as mean and standard deviation (SD) in
194 the text and standard error (SE) in the figures. Statistical analyses were performed with SPSS
195 Version 22.0 (IBM Corp., Armonk, NY, USA). Statistical significance was set at $p < 0.05$.

196

197

198

199

200 **RESULTS**

201 *Sensory characteristics*

202 Peak pain intensity was greater following the injection of hypertonic (5.5 ± 1.8) compared to
203 isotonic saline (0.9 ± 0.8 , $p < 0.00001$; Figure 2). Pain duration and area were significantly greater
204 following hypertonic compared to isotonic saline injection (both $p < 0.00001$). Total mapped pain
205 areas were 0.25 ± 0.18 and 0.02 ± 0.05 (arbitrary units) for the hypertonic and isotonic saline
206 injections respectively.

208 *Electromyography*

209 Figure 3 illustrates the average EMG amplitude (averaged across the entire grid of
210 electrodes) for each of the four conditions. An overall reduction in the amplitude of upper trapezius
211 activity is evident in the painful condition compared to the other conditions. Consistent with this
212 observation, the mean RMS was dependent on the interaction between condition and stage of the
213 cyclic movement ($F=8.5$, $p < 0.00001$). The mean RMS was lower during the painful condition
214 compared to baseline, post and recovery during stages 30-70% of the cyclic movement (SNK: all
215 $p < 0.05$; Figure 3), stages when the muscle should have been most active.

216 The y-axis coordinate of the centroid of the EMG map was also significantly dependent on
217 condition ($F=7.5$, $p < 0.001$) with higher values observed during the painful condition compared to
218 all other conditions (SNK: all $p < 0.01$; Figure 4). This indicates that center of activity was shifted in
219 the caudal direction in the painful condition. No differences were observed between the baseline,
220 isotonic or recovery conditions ($p > 0.05$).

221 Figure 5 provides representative EMG amplitude maps from a single subject extracted at
222 60% of the cycle for the four conditions. Note the overall reduced EMG amplitude and shift of
223 activity away from the cranial direction in the painful condition. On the contrary the x-axis
224 coordinate of the centroid of the EMG map did not differ between conditions ($p > 0.05$; Figure 6).

Figure 7 illustrates the entropy measured from the EMG amplitude maps recorded for each cycle of the task from a single representative subject for all four conditions. Note that the EMG amplitude becomes more uniform in the painful condition. Accordingly, the entropy of the EMG amplitude was dependent on the interaction between condition and stage of the cyclic movement ($F=2.5$, $p<0.001$) with a higher percentage of entropy observed during the painful condition compared to all other conditions at stages 30-80% of the cyclic movement (SNK: all $p<0.01$; Figure 8). Entropy was also higher for the painful condition at stage 20% of the cycle compared to the isotonic and recovery conditions (SNK: both $p<0.05$).

DISCUSSION

Noxious stimulation of the upper trapezius resulted in a shift of the distribution of activity towards the caudal region of the muscle during performance of a repetitive lifting task. This change in the distribution of activity to different regions of the muscle may have important implications for the perpetuation and worsening of neck-shoulder pain during repetitive tasks.

During the baseline and control conditions, there was a general increase in the amplitude of upper trapezius activity during the lifting phase of the task (stages ~30-70%). This was expected and is in line with the anatomical action of the muscle. Activation of the upper trapezius is essential for normal scapulohumeral rhythm during arm elevation¹⁹. Normal scapulohumeral rhythm requires upward rotation of the scapula which is provided by the force couple of the trapezius and serratus anterior, in order to prevent the rotator cuff tendon from impinging against the anterolateral acromion^{19,20}. Moreover, the results revealed a shift in the distribution of activity towards the cranial region of the muscle during the elevation phase of the task. The relative adaptations in the intensity of activity within muscle regions may be attributed to variation in peripheral properties or in the control of motor units within a muscle. For example, since muscle fibers within the upper trapezius have non-uniform morphological and histological properties²¹, an increase in the neural drive to the muscle would result in preferential activation of specific muscle regions. Most likely,

251 motor unit recruitment or the discharge rate of the active motor units varied within the different
252 regions of the muscle^{22,23}. The cranial shift in the distribution of upper trapezius activity likely
253 reflects a shift in activation towards the muscle fibers which have a better mechanical advantage to
254 generate the upward rotation and elevation of the scapula with arm elevation. This pattern of upper
255 trapezius muscle activation during the repetitive task was consistent between the baseline and
256 control conditions and is in agreement with the characteristic increase in surface EMG amplitude
257 towards the cranial region of the upper trapezius muscle with increasing force²⁴.

258 An overall reduction of upper trapezius activity was observed following noxious stimulation
259 of the upper trapezius muscle. This observation is line with several studies which demonstrated that
260 injection of hypertonic saline (experimental muscle pain), which excites nociceptive muscle
261 afferents (group III and IV), reduces the activation of the painful muscle^{13,25-27}. Reduced muscle
262 activation implies that the nociceptive input reduced the net excitatory input to the population of
263 motor neurons^{28,29} which is likely due to decreased descending drive to the muscle or to pure spinal
264 mechanisms, or more likely, a combination of both.

265 Novel to this study, we also observed a shift of the distribution of upper trapezius activity
266 during performance of the repetitive task. Specifically, the center of trapezius muscle activity was
267 shifted more caudally in the painful condition. This implies that regions of the muscle which would
268 not normally be as active, became active in the painful condition and that regions which would
269 normally be active (based on their anatomical action) became less active. This change resulted in
270 more uniform activation of the upper trapezius muscle as seen from the entropy data. This new
271 motor strategy may be seen as effective mechanism to “protect” the painful region^{30,31}. However,
272 based on anatomical considerations, the “new” pattern of trapezius muscle activation in the painful
273 condition can be seen as inefficient motor strategy. Previous investigations of the distribution of
274 upper trapezius muscle activity using high-density EMG have observed a shift in the distribution of
275 activation towards the caudal region of the muscle during painful conditions, albeit during isometric
276 shoulder abduction¹²⁻¹⁴. Additionally, people with fibromyalgia display activation of their upper

277 trapezius which is centered more caudally compared to pain-free participants during sustained
278 shoulder abduction ¹⁷. Moreover, a recent study of people with low back pain showed that patients
279 performed a repetitive task with a different distribution of lumbar erector spinae muscle activity
280 compared to pain-free volunteers ³². Although there may be a short term benefit of such an adaption
281 as it allows the person to complete the motor task, the long term consequence of these altered motor
282 strategies may be overload of muscle fibers and as a further consequence, perpetuation or
283 recurrence of pain.

284 Hodges and Tucker ³¹ proposed a theory of motor adaptation to pain, which explained a
285 large number of findings that were not fully explained by previous theories such as the Pain
286 Adaptation ³³ or Vicious Cycle ³⁴ theories. One element of this new theory is that muscle activity is
287 redistributed to minimize activity of the painful region with the aim of “protecting” the painful area.
288 The current results support this theory since the shift of activity was away from the site of local
289 noxious stimulation. However, other work has shown a shift of the distribution of muscle activity
290 towards the caudal (painful) region of the upper trapezius during isometric shoulder abduction even
291 when the site of noxious stimulation is in the caudal region ¹³. Motor units in the caudal region of
292 the upper trapezius have greater discharge rates during sustained shoulder abduction than motor
293 units in cranial regions ²²⁻²³ which suggests that motor units in the caudal region have lower
294 recruitment thresholds than those in the cranial region. Since nociception decreases the net
295 excitatory drive to the motor neurons ^{28,29}, the presence of pain in the upper trapezius is expected to
296 reduce muscle activity predominantly in the cranial region, where motor units have higher threshold
297 for activation. Thus when the upper trapezius muscle is painful, regardless of the location of pain,
298 the adaptation of the upper trapezius aims preferentially to minimize activation of the cranial
299 region; possibly because this region has higher pain sensitivity ³⁵.

300 *Clinical considerations*

301 Repetitive movement is a physical risk for work-related musculoskeletal disorders including
302 those of the neck-shoulder region ³⁶. The proportion of workers exposed to repetitive arm

303 movement continues to increase³⁷. Needless to say, musculoskeletal disorders located in the neck–
304 shoulder region are associated with substantial socio-economic consequences³⁶. Changes in the
305 activation of upper trapezius have been observed in people with neck-shoulder disorders and
306 include altered activation during repetitive tasks³⁸⁻⁴⁰ and computer work⁴¹, reduced ability to relax
307 the upper trapezius following voluntary activation³⁹ and reduced rest periods of the upper trapezius
308 during repetitive tasks⁴². Given the common complaint of upper trapezius muscle pain and the
309 alterations of upper trapezius activity which have been frequently documented in people with neck-
310 shoulder disorders, further studies investigating the basic effect of nociception on the activation of
311 the trapezius muscle have been needed to better understand the potential associations between
312 repetitive movement, pain and altered motor control. By applying state of the art, high-density
313 surface EMG, the current work revealed a change in the distribution of upper trapezius activity
314 during repetitive work when pain is present. These findings may be relevant for interpreting
315 changes in trapezius activity in clinical pain conditions and offer further insight into the hypothesis
316 of overload of muscle regions and overexertion of low-threshold motor units in the presence of
317 upper trapezius pain⁴³.

318

319 *Methodological considerations*

320 It is likely that the noxious stimulation of the upper trapezius induced a reorganization of the
321 activation of other neck, shoulder and/or scapular muscles^{25,45}. However, we preferred to have
322 more channels placed over the trapezius muscle in order to generate a larger mapping of trapezius
323 muscle activity rather than having a reduced number of electrodes spread over multiple muscles.
324 Since upper trapezius activity changed in the painful condition, it is also possible that scapular
325 motion was altered during the lifting task. Motion analysis of the upper quadrant may have
326 strengthened the current observations. The lack of kinematic analysis of task performance does not
327 allow us to conclude that the task was performed in exactly the same way in the painful condition
328 i.e. that the subjects were doing the same movements, although using different muscle patterns.

329 Even though the general posture and performance of the subjects were monitored throughout by
330 investigators to ensure consistency, we cannot exclude subtle variations in movement between
331 conditions. Nonetheless, other studies using more constrained tasks have confirmed that the
332 kinematics of the task can remain the same in painful and control conditions despite reorganization
333 of muscle activation ^{25,45}.

334 The electrode grid was positioned in order to be within the region of the upper trapezius and
335 achieve coverage of a large proportion of the upper trapezius in the longitudinal direction. In some
336 cases the electrode grid may have covered a portion of the middle division of trapezius. However
337 this would not affect the main conclusion of the study, as the middle fibers of the trapezius are not
338 anatomically suited to provide scapular elevation with arm elevation.

339 Experimental muscle pain provides a means to explore the effect of nociception on motor
340 control in the absence of pathological changes within the muscle and joint. Thus for the purposes of
341 the current study, this approach allowed us to specifically evaluate the effect of nociception on the
342 distribution of upper trapezius muscle activity. However, different results may be seen in people
343 with work-related neck-shoulder pain, especially in people with high levels of kinesiophobia where
344 their motor strategy may be altered in a different way due to fear of pain provocation with
345 movement. Although the sample size was small it is in line with previous experimental pain studies
346 however, it should be noted that the subjects were young men and the results cannot necessarily be
347 generalized to women or older persons. This is a limitation of the study especially considering the
348 higher prevalence of trapezius myalgia in women ⁵. Finally, a potential further limitation of the
349 study is that the order of the injections was not randomized although, the participants were advised
350 that one or both could be painful. Moreover a recovery condition was included.

351

352 *Conclusion*

353 Repetitive tasks are an important risk factor for initiation, maintenance and recurrence of neck-
354 shoulder pain. This study revealed a different distribution of upper trapezius activity when a repetitive

355 lifting task was performed in the presence of pain. This knowledge provides new insights into the
356 mechanisms underlying the perpetuation of pain with repetitive activity.

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362 **Contributors:** DF, CC, RL contributed to the conception and design of the study. CC and RL
363 collected the data. CC, DF and MB analysed the data. DF and MB wrote the first draft of the paper.
364 All authors contributed to the interpretation of findings, revising the manuscript for important
365 intellectual content, and approved the final version to be published. All authors had full access to all
366 of the data (including statistical reports and tables) in the study and can take responsibility for the
367 integrity of the data and the accuracy of the data analysis.

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529 **FIGURE LEGENDS**

530

531 **Figure 1:** High-density surface EMG signals were detected using a semi-disposable adhesive grid
532 of electrodes over the right upper trapezius muscle. The grid consists of 13 rows and 5 columns of
533 electrodes with one electrode absent at the upper right corner. The electrode grid was placed with
534 the 4th row along the C7-acromion line. The injection was performed lateral to the electrode grid (~
535 10 mm) 15 mm cranial to the line between the acromion and the spinous process of the seventh
536 cervical vertebra.

537

538 **Figure 2:** Mean (+ SE) pain intensity scores following injection of 0.4 ml of hypertonic saline and
539 0.4 ml of isotonic saline into the cranial of the upper trapezius.

540

541 **Figure 3:** Mean (\pm SE) of the average root mean square (RMS) estimated for each stage of the
542 repetitive lifting task. Each cycle was divided in 10 epochs of equal length and the EMG signals
543 were analyzed separately for each epoch of each cycle. The EMG variables were then averaged
544 across the 50 cycles for each epoch of the cycle. Data are expressed in percentages (0-100%) with
545 respect to the cycle duration. Significant difference between hypertonic saline condition compared
546 to baseline: * $p < 0.05$; significant difference between hypertonic saline condition compared to
547 isotonic saline condition: # $p < 0.05$; significant difference between hypertonic saline condition
548 compared to recover condition: ‡ $p < 0.05$.

549

550 **Figure 4:** Mean (\pm SE) of the y-axis coordinate of the centroid of the RMS map estimated for each
551 stage of the repetitive lifting task. Each cycle was divided in 10 epochs of equal length and the
552 EMG signals were analyzed separately for each epoch of each cycle. The EMG variables were then
553 averaged across the 50 cycles for each epoch of the cycle. Data are expressed in percentages (0-
554 100%) with respect to the cycle duration. Significant difference between hypertonic saline

555 condition compared to baseline: * $p < 0.01$; significant difference between hypertonic saline
556 condition compared to isotonic saline condition: # $p < 0.01$; significant difference between
557 hypertonic saline condition compared to recover condition: ‡ $p < 0.01$.

558

559 **Figure 5:** Representative topographical maps (interpolation by a factor 8) of the EMG root mean
560 square (RMS) value recorded for one subject during the stage 60% of the repetitive lifting task at
561 baseline, following the injection of isotonic saline and hypertonic saline into the cranial region of
562 the upper trapezius and following 15 min of rest after the last injection (recovery). Colors are scaled
563 between the minimum and maximum RMS values. Areas of dark blue correspond to areas of low
564 EMG amplitude and dark red to areas of high EMG amplitude. Note the overall decrease of EMG
565 amplitude in the painful condition (hypertonic) and the general shift of activity towards the caudal
566 region of the muscle.

567

568 **Figure 6:** Mean (\pm SE) of the x -axis coordinate of the centroid of the RMS map estimated for each
569 stage of the repetitive lifting task. Each cycle was divided in 10 epochs of equal length and the
570 EMG signals were analyzed separately for each epoch of each cycle. The EMG variables were then
571 averaged across the 50 cycles for each epoch of the cycle. Data are expressed in percentages (0-
572 100%) with respect to the cycle duration. No significant differences were identified.

573

574 **Figure 7:** Representation of entropy of EMG amplitude maps during each portion of each cycle in
575 the four conditions of a representative subject. Each pixel of the map represents the entropy of the
576 RMS map. Each column corresponds to each of the lifting cycles while each row represents a
577 portion of the cycle. Each cycle was divided in 20 epochs of equal length for graphical reasons.
578 Baseline, Isotonic and Recovery conditions show similar patterns of entropy with lower values
579 between 30% and 60% of each cycle while the Hypertonic conditions shows higher values and a
580 different distribution of values.

581

582 **Figure 8:** Mean (\pm SE) of the entropy (%) of the RMS map estimated for each stage of the
583 repetitive lifting task. Each cycle was divided in 10 epochs of equal length and the EMG signals
584 were analyzed separately for each epoch of each cycle. The EMG variables were then averaged
585 across the 50 cycles for each epoch of the cycle. Data are expressed in percentages (0-100%) with
586 respect to the cycle duration.

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